New methods to remove baseline drift in trapezoidal pulse shaping*

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Trapezoidal pulse shaping algorithm is widely applied to improve signal-to-noise ratio (SNR), throughput and energy resolution with the properties of noise suppression, pile-up pulse separation and ballistic deficit correction. The algorithm can be acquired by z transform method which is easier for derivation. However, the baseline drift of trapezoidal pulse appears because the noise superimposes on the input signal. In this paper, two new methods based on convergence analysis and noise suppression are proposed to remove the baseline drift resulting from trapezoidal pulse shaping. Simulations and experimental tests are carried out to verify the methods. The results demonstrate that the proposed methods can remove baseline drift in trapezoidal pulse shaping.

Keywords: Baseline drift removal, Trapezoidal pulse shaping, z transform method

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I. INTRODUCTION

Digital pulse shaping algorithm is a main contents of digital spectrometer. They are injected to realize pulse shaping in field programmable gate array (FPGA). Trapezoidal pulse, with its rise time being equal to the fall time, provides a near optimum signal-to-noise ratio (SNR). The flat top of trapezoidal pulse can be flexibly set to adapt different measurement conditions. Therefore, trapezoidal pulse shaping algorithm is widely applied to improve SNR, throughout and energy resolution.

The theory of trapezoidal pulse shaping has been well developed and published. Radeka designed a trapezoidal filter based on a gated filter system, which achieved good resolution with large germanium detectors at high counting rates and higher energies [1]. Jordanov *et al*. developed the recursive algorithm of trapezoidal pulse shaping by using a convolution method [2, 3]. The algorithm based on convolution method made trapezoidal pulse shaping possible by digital means. Stein *et al*. used moving window deconvolution technique to realize trapezoidal and triangular shaping in digital signal processor (DSP) [4]. In addition, a real time digital pulse shaper, which was synthesized by a concave and a convex pulse shapes, was also implemented in programmable logic [5]. Also, z transform method was described to obtain the recursive algorithm of trapezoidal pulse shaping by Cosimo Imperiale [6]. Some simulations of the algorithm based on z transform method were discussed [7–10]. Recently, Trapezoidal shaper was employed in digital spectrometer for ballistic deficit correction, neutron-gamma discrimination and pile up correction [11, 12]. Furthermore, typical shapers, including triangular, trapezoidal and cusp-like ones, were generated in a new adaptive digital shaper which enabled automatic adjustment of coefficients for shaping an input signal [13]. However, when the input signal is associated with noise, the baseline drift of trapezoidal pulse appears. It is especially obvious in the process of consecutive pulses. In this paper, we propose two methods to remove the baseline drift. The feasibility and accuracy of the methods are verified by simulations and experiments. The results show that the methods can remove the baseline drift in trapezoidal pulse shaping.

II. TRAPEZOIDAL PULSE SHAPING

The trapezoidal pulse shaping algorithm was raised by z transform method [6]. As shown in Fig. 1, a trapezoidal pulse can be directly synthesized by Eq. (1):

$$v_o = \sum_{i=1}^{4} v_i(t), \tag{1}$$

where, $v_1(t) = (V_{\max}/t_a)\cdot tu(t)$, $v_2(t) = -v_1(t-t_a)u(t-t_a)$, $v_3(t) = -v_1(t-t_b)u(t-t_b)$, and $v_4(t) = v_1(t-t_c)u(t-t_c)$; t_a is the rise time of trapezoidal pulse, $t_b - t_a$ is the duration of flat top, t_c is the total width of pulse, and $V_{\max}$ is the height.

Equation (1) can be described as Eq. (2) according to z transform

$$V_o(z) = \frac{V_{\max} z(1 - z^{-n_a} - z^{-n_b} + z^{-n_c})}{n_a(1 - z^{-1})^2}, \tag{2}$$

where, $n_a = t_a/T_s$, $n_b = t_b/T_s$, $n_c = t_c/T_s$, and T_s is the sampling time of ADC. The input signal is defined as

$$v_i(t) = Ae^{-t/\tau}u(t) \qquad t \geq 0, \tag{3}$$

where A is the height and τ is the time constant. The function of the input signal in z transform notation is

$$V_i(z) = A \cdot \frac{1}{1 - dz^{-1}}, \tag{4}$$

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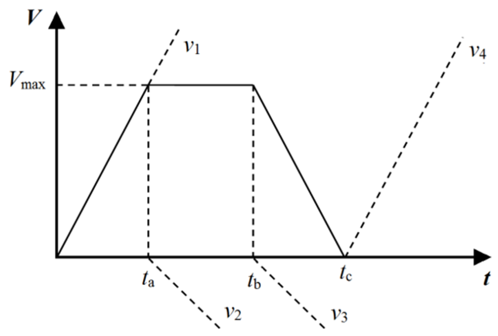

Fig. 1. Synthesis of trapezoidal pulse.

where $d = e^{-T_s/\tau}$. The transfer function of Fig. 1 can be represented as

$$H(z) = \frac{V_o(z)}{V_i(z)} = \frac{(1-dz^{-1})(1-z^{-n_a})(1-z^{-n_b})z^{-1}}{n_a(1-z^{-1})^2}, \tag{5}$$

then

$$V_o(z)(1-z^{-1})^2 = V_i(z)\cdot\frac{(1-dz^{-1})(1-z^{-n_a})(1-z^{-n_b})z^{-1}}{n_a}. \tag{6}$$

Applying inverse z transform, we have the time domain output of v_o:

$$\begin{cases} v_o[n] = 2v_o[n-1] - v_o[n-2] + \{v_i[n-1] - v_i[n-n_a-1] - v_i[n-n_b-1] + v_i[n-n_c-1] - d\cdot[v_i[n-2] \\ \qquad - v_i[n-n_a-2] - v_i[n-n_b-2] + v_i[n-n_c-2]]\}\cdot\dfrac{1}{n_a} \\ v_o[n] = v_i[n] = 0 \qquad n \le 0 \end{cases}. \tag{7}$$

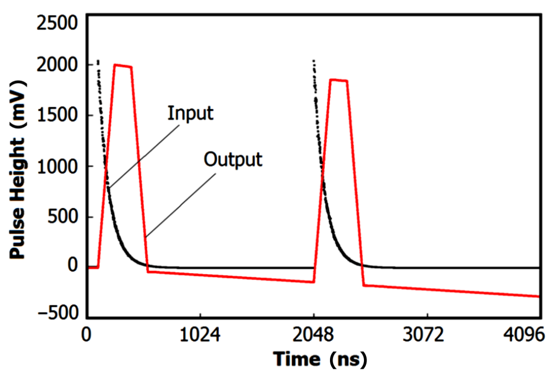

Fig. 2. (Color online) Trapezoidal pulse shaping with baseline drift.

The trapezoidal pulse shaping is implemented by Eq. (7). It is suitable for processing ideal input signal without noise. Generally, the input signal is superimposed by Gaussian white noise. An input signal with SNR = 30 dB is simulated by Eq. (3) with $A = 2000$ and $\tau = 100$. The result of trapezoidal pulse shaping with $n_a = 150$, $n_b = 300$, $n_c = 450$, $T_s = 1$ is shown in Fig. 2. The baseline drift of trapezoidal pulse appears when the input signal is associated with Gaussian white noise. The simulations results indicate that the lower SNR, the more serious baseline drift will be.

III. SIMULATIONS AND EXPERIMENTAL TESTS

A. Convergence conditions

Figure 2 shows that the algorithm based on z transform method is not convergent. To remove the baseline drift, a new method based on convergence analysis is used. Letting $y[n] = v_o[n]$ and $x[n] = v_i[n]$, Eq. (7) can be written as

$$y[n] = 2y[n-1] - y[n-2] + X[n], \tag{8}$$

where

$$X[n] = \frac{1}{n_a}\cdot\{x[n-1] - x[n-n_a-1] - x[n-n_b-1] + x[n-n_c-1] - d\cdot[x[n-2] - x[n-n_a-2] - x[n-n_b-2] + x[n-n_c-2]]\}.$$

The recursive equations of Eq. (8) are as follows:

$$\begin{aligned} y[n] - y[n-1] &= y[n-1] - y[n-2] + X[n] \\ y[n-1] - y[n-2] &= y[n-2] - y[n-3] + X[n-1] \\ y[n-2] - y[n-3] &= y[n-3] - y[n-4] + X[n-2] \\ &\vdots \\ y[3] - y[2] &= y[2] - y[1] + X[3] \\ y[2] - y[1] &= y[1] - y[0] + X[2]. \end{aligned}$$

An equation only about $y[n]$, $y[n-1]$, $y[1]$, $y[0]$ and $X[n]$ is acquired by accumulating the equations above

$$y[n] - y[n-1] = y[1] - y[0] + \sum_{i=2}^{n} X[i].$$

The general formula of $y[n]$ is

$$y[n] - y[1] = (n-1)(y[1]-y[0]) + X[2] + \sum_{i=2}^{3} X[i] + \cdots + \sum_{i=2}^{n-1} X[i] + \sum_{i=2}^{n} X[i]. \tag{9}$$

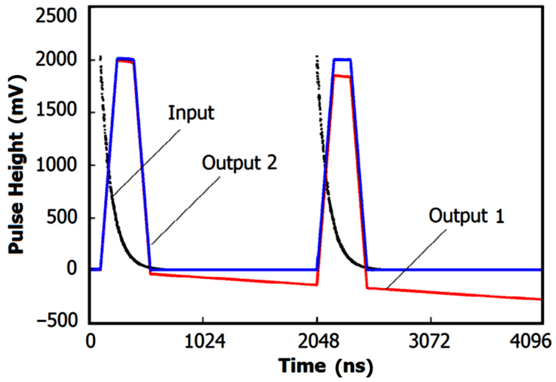

Fig. 3. (Color online) Baseline drift removal based on the new method.

Assuming that $y[0] = y[1] = 0$, one can simplify Eq. (9) into Eq. (10):

$$y[n] = X[2] + \sum_{i=2}^{3} X[i] + \cdots + \sum_{i=2}^{n-1} + \sum_{i=2}^{n} X[i]. \quad (10)$$

$v_i[n]$ is an equal ratio progression, with an equal ratio of $q = e^{-1/\tau}$. It can be proved that $X[n]$ is also an equal ratio progression and the equal ratio is q. Equation (10) is expressed as

$$y[n] = X[2] + \frac{X[2](1-q^2)}{1-q} + \cdots + \frac{X[2](1-q^{n-2})}{1-q} + \frac{X[2](1-q^{n-1})}{1-q}. \quad (11)$$

Let $y[n] = X[2] + Y$, where

$$Y = C \cdot (1-q^2) + \cdots + C \cdot (1-q^{n-2}) + C \cdot (1-q^{n-1}),$$

where $C = X[2]/(1-q)$, and then

$$Y = C[n-2-q^2(1-q^{n-2})/(1-q)]. \quad (12)$$

$q < 1$ as $\tau > 1$. So, $y[n]$ can be convergent when $Y = 0$. It can be seen from Eqs. (8) and (12) that Y can be set to 0 by setting $x[1]$ to 0. Figure 3 illustrates the result of trapezoidal pulse shaping with $v_i[1] = 0$, with the same input signal as Fig. 2. Output 1 is used as a contrast. Output 2 is the trapezoidal pulse with the first input data being 0. Therefore, the new method can remove the baseline drift resulting from trapezoidal pulse shaping.

B. Noise suppression

The baseline drift of trapezoidal pulse is caused by noise accumulation. Filtering the original signal before shaping is another way of removing the baseline drift. Digital S-K filter performs well in signal processing with amplitude filtering and frequency filtering factors [14]. The true height of filtered signal can be obtained by adjusting amplitude of the filtering factor properly. The algorithm of digital S-K filter is written as

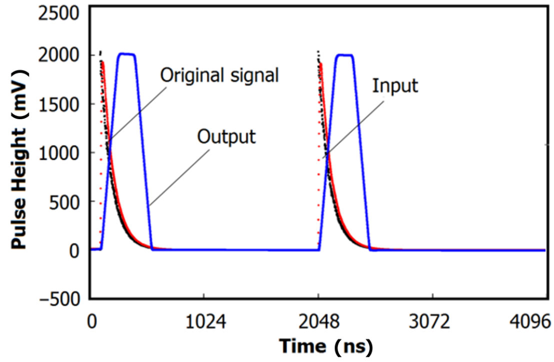

Fig. 4. (Color online) Digital S-K filter in trapezoidal pulse shaping.

$$\begin{cases} y[n] = \frac{(k\cdot(3-a)+2k^2)\cdot y[n-1] - k^2\cdot y[n-2] + a\cdot x[n]}{1+k\cdot(3-a)+k^2} \\ y[n] = x[n] = 0 \qquad n \le 0 \end{cases}, \quad (13)$$

where $x[n]$ is the discrete input signal, $y[n]$ is the output signal, k is the frequency filtering factor and a is the amplitude filtering factor. The original signal in Fig. 2 is filtered by the digital S-K filter, and output of the filter is processed by calling Eq. (7) recursively. The baseline drift of trapezoidal pulse is removed with $k = 5$, $a = 1.15$, as shown in Fig. 4.

Differential operation can also attenuate the noise. Equation (6) can be rewritten as

$$V_o(z) = V_i(z) \cdot \frac{(1-dz^{-1})(1-z^{-n_a})(1-z^{-n_b})z^{-1}}{n_a(1-z^{-1})^2}. \quad (14)$$

Assuming $V(z) = V_i(z)/(1-1/z)^2$, an improved recursive algorithm of trapezoidal pulse shaping is obtained:

$$\begin{cases} v[n] = 2v[n-1] - v[n-2] + v_i[n] \\ v_o[n] = \frac{1}{n_a} \cdot \{v[n-1] - v[n-n_a-1] - v[n-n_b-1] + v[n-n_c-1] \\ \qquad - d \cdot (v[n-2] - v[n-n_a-2] - v[n-n_b-2] + v[n-n_c-2])\} \\ v_o[n] = v[n] = 0 \qquad n \le 0 \end{cases}. \quad (15)$$

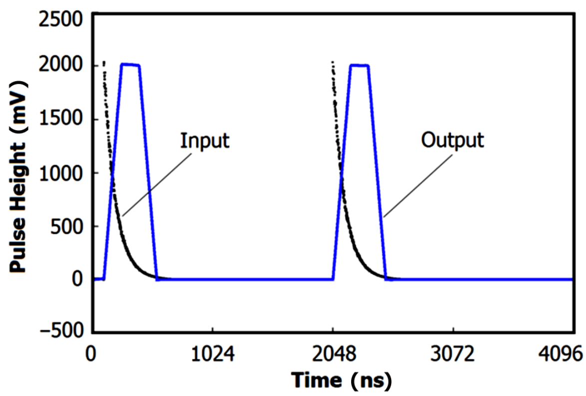

Fig. 5. (Color online) Trapezoidal pulse shaping based on the improved recursive algorithm.

Equation (15) is the improved recursive algorithm of trapezoidal pulse shaping without baseline drift [10]. Trapezoidal pulse can be implemented by calling Eq. (15). Figure 5 shows that the improved algorithm can remove the baseline drift in Fig. 2.

C. Measured pulses shaping

In order to verify feasibility of the methods, pulses tests were carried out. The time constant of pulses is 3.2 µs, detected by silicon drift diode (SDD) detector and digitized by ADC at 20 MSPS, with $T_s = 50\,\text{ns}$ and $\tau = 3.2\,\mu\text{s}$ according to Eq. (7). A trapezoidal pulse with $t_a = 4\,\mu\text{s}$, $t_b = 4\,\mu\text{s}$ and $t_c = 8\,\mu\text{s}$ corresponding to $n_a = 80$, $n_b = 80$ and $n_c = 160$ is implemented by Eqs. (7) and (15). The experimental tests of different methods are given in Fig. 6.

The results indicate that both the new method and the improved recursive algorithm can remove the baseline drift in trapezoidal pulse shaping. For the purpose of signal filtering, digital S-K filter can also be used in trapezoidal pulse shaping to remove baseline drift. However, it is complex to realize digital S-K filter in FPGA. Besides, it is also difficult to select the values of k and a. Therefore, the new method and the improved recursive algorithm are recommended in practical applications. The correlation between the new method and the improved recursive algorithm is shown in Fig. 7. It indicates that the improved method is suitable for trapezoidal pulse shaping without baseline drift.

IV. CONCLUSION

In this paper, the recursive algorithm of trapezoidal pulse shaping is derived by z transform method and the approaches to baseline drift removal are discussed. Setting the first input data to 0 and digital S-K filter are used to remove the baseline drift due to the accumulation of noise. The results of experimental tests demonstrate that the methods can remove the baseline drift existing in trapezoidal pulse shaping.

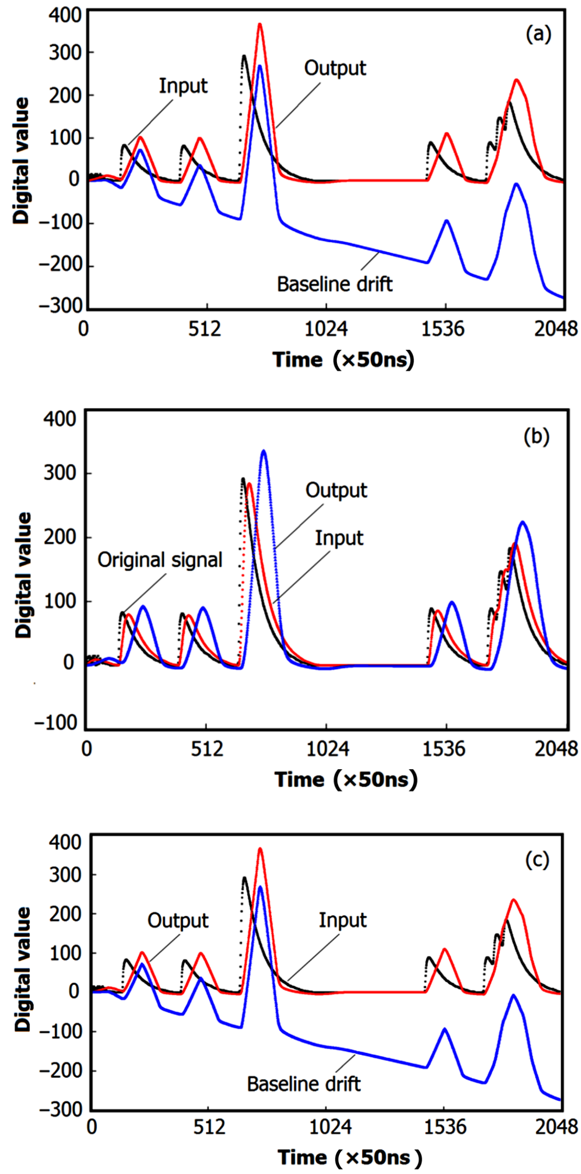

Fig. 6. (Color online) Pulses shaping with (a) the first input data being 0, (b).digital S-K filter processing and (c) the improved recursive algorithm.

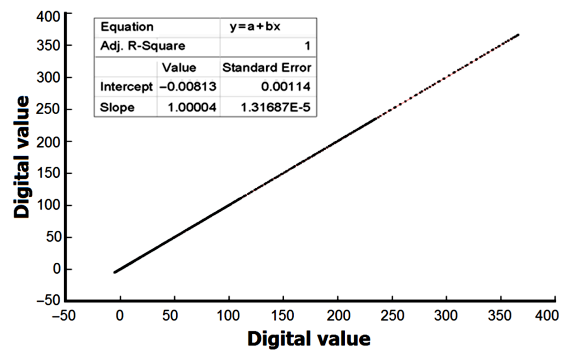

Fig. 7. (Color online) Correlation between the new method and the improved recursive algorithm.

A comparison between the new method and the improved recursive algorithm is also carried out. It shows that the new method has a good linear relationship with the improved recursive algorithm. The new method is recommended for real time trapezoidal pulse shaping.

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